# The latitudinal distribution of solar wind magnetic holes

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**Abstract.** Using the fast latitude scan period of the Ulysses spacecraft, the occurrence of magnetic holes in the solar wind is investigated from -80° to +80° helio-latitude. Near the ecliptic, the large average value and the large variations of the hole count rate appear to be correlated with interaction regions. It is found, however, that at 30°north and south latitude, approximately, the hole count rate drops to about 10% of that in the low latitude region and stays constant at this level to near the poles. The small but non-zero hole count rate at high helio-latitudes indicates that these holes were formed by processes other than the large scale dynamic solar wind features operating in the ecliptic region.

## Introduction

Localized depressions in the magnitude of the interplanetary magnetic field (IMF) were first observed in 1971 by Explorer 43 [*Turner et al.*, 1977]. These "magnetic holes" were distinct entities in otherwise average IMF conditions; i.e., they were not random depressions in a region of noisy or weak fields. Previously, a large number of magnetic holes had been found in the Ulysses data during its cruise in the ecliptic [*Winterhalter et al.*, 1994a]. On average about 50 linear holes (with magnetic field rotation $\leq 10°$) were observed per month. The magnetic holes were shown to be pressure-balanced, convecting structures, having a typical width of 10 to 15 seconds, and a depth down to a typical value of 0.01 nT and lower. Figure 1 shows two examples of linear magnetic holes.

Figure 1

A major result in *Winterhalter et al.* [1994a] was the conclusion that the magnetic holes in the solar wind are probably relics of the mirror instability. The reasons are: (1) The dip in field strength is accompanied by a simultaneous increase in plasma density and pressure. (2) The holes are found in high $\beta$ plasma that is significantly less stable to the mirror mode than most of the solar wind. (3) Plasma with trains of closely spaced magnetic holes is often marginally mirror-mode stable. (4) There is sometimes a similarity of the squared-off velocity-space contours observed within the holes to distribution functions derived from numerical simulations of mirror-mode waves.

A high $\beta = nkT/(B^2/8\pi)$ plasma with anisotropic temperatures is unstable to the mirror mode. But once the instability has occurred and the plasma becomes (marginally) stable, the mirror mode structure evolves into a magnetic hole that is convected downstream to the point of observation. The characteristics of the holes reflect the solar wind conditions of the upstream region in which the holes are formed. Recent theoretical descriptions of the mirror mode [*Kivelson et al.*, 1996; *Southwood et al.*, 1993], and modeling results [*Pantellini et al.*, 1998] have supported this interpretation. The apparent ubiquity of the magnetic holes suggests that the mirror instability is an important mechanism by which the solar wind plasma progresses toward isotropy.

The previous studies have all used data from near the ecliptic. It was found that there, in a statistical sense, the number of holes per day is more or less independent of heliospheric distance, regardless of the appearance and disappearance of particular large scale solar wind structures. On the other hand, in a set of prominent examples selected for further study, a large fraction of holes occurred in interaction regions [*Winterhalter et al.*, 1994a]. With the progression of Ulysses to high heliographic latitudes the interaction regions have disappeared, and only a relatively quiet, high speed solar wind is present above 57°latitude [*Phillips et al.,* 1995]. This presents an opportunity to disentangle the contribution by interaction regions from those produced by other sources. The purpose of this paper is to ascertain whether the holes persist at higher latitude.

## Data and Analysis

The data used for this study is from the period when the Ulysses spacecraft executed its "fast latitude scan". The interval started in September 1994 and lasted for about one year. During this time Ulysses moved from the sun's rotational south pole region, near -80°, to the near the north pole, +80°, (Figure 2). Radially the spacecraft moved from about 2.2 AU to 1.3 AU, and back out to 2.2 AU, i.e., the radial excursion was less than 1 AU.

Figure 2

We use 2-second averaged data from the Ulysses magnetometer experiment, described by *Balogh et al.* [1992]. In addition, solar wind speed data (one hour averages) was used from the Ulysses solar wind plasma experiment (SWOOPS). The design and operation of SWOOPS are described by *Bame et al.* [1992].

Using a procedure identical to the one used in the previous studies [*Winterhalter et al.,* 1994a], we electronically scanned the magnetic field data for the fast latitude scan interval. A hole was defined (arbitrarily) to be a dip in the field strength such that $B_{min}/B_0 \leq 0.5$, where $B_{min}$ and $B_0$ are the minimum and average field magnitudes within a sliding window 300 seconds in length. In this study the selected holes were restricted to those with field rotation $\delta\theta$ across the hole less than $10°$. This is done to avoid any confusion with Alfvén waves, or heliospheric plasma sheet crossings [*Winterhalter et al.*, 1994b], or other unrelated events. All in all, we found 4620 linear holes.

The holes were then counted in each one-day interval during the fast latitude scan period, to arrive at $N/\Delta t$, the number of holes per day (Figure 3). It is seen that there are typically 5 or so holes per day, across all latitudes. The variation is large, however, also on the order of 5 holes per day. In addition, there are some large spikes near the ecliptic. No unambiguous answer as to whether or not the hole occurrence is latitude dependent can be obtained from this figure.

Figure 3

One reason for this is the well known change of the solar wind speed with latitude [*Phillips et al.*, 1995], with the high speed of typically 800 km/s present in high latitudes, and 400 km/s being typical near the ecliptic. Thus when counting the holes for one hour the Ulysses spacecraft will sample more solar wind at high latitudes than it will at low latitudes.

We correct for this by normalizing the count with respect to the solar wind speed, $V_{sw}$, so that N/L $\approx N/(\Delta t V_{sw})$, where $N/\Delta t$ is the number of holes per hour, and L is some length scale. We choose (arbitrarily) L to be one solar radius, $R_s$. Thus by normalizing with the solar wind speed, we count the holes contained in a piece of solar wind one solar radius long.

The exact data analysis procedure was 1) to count the number of holes per hour, 2) to average $V_{sw}$ for any given hour and calculate N/$R_s$, and 3) find the average latitude of Ulysses for any given hour. 4) to calculate the averages of N/$R_s$ in 1°bins of latitude. The result is shown in Figure 4.

Figure 4

Figure 4 shows that the hole count is essentially anticorrelated with the solar wind speed. In the low speed equatorial region the count spikes up to 4 or 5 holes per solar radius, from a background of $\approx 0.5/R_s$. At higher heliographic latitude ($\Phi$), when $|\Phi| > 30°$and where the solar wind speed $V_{sw} \approx 800$ km/s, the hole count stays at that same background with little variation. Further, there is no evidence for a trend in the hole count as a function of latitude. Thus the solar wind emanating from polar coronal holes contains few magnetic holes (one evey two $R_s$).

## Discussion

The occurrence of magnetic holes was analyzed during a period (fast latitude scan) when the Ulysses spacecraft moved from nearly pole to pole over the sun, while changing its radial distance from the sun by a relatively small amount (the occurrence rate appears to be constant with heliocentric distance, at least out to 5 AU; see *Winterhalter et al.* [1994a]. Thus the variations in the occurrence rate are due to the latitudinal changes in the solar wind character.

Figure 4 shows two interesting features of the magnetic hole occurrence. The first pertains to the large increases at low heliographic latitude. Qualitatively, the increases in the hole count occur in regions of large velocity gradients, commensurate with the conclusion in *Winterhalter et al.* [1994a] that a significant fraction of low-latitude holes occur in interaction regions. In particular, near the leading edges of high-speed streams associated with coronal streamers [*Gosling et al.,* 1981] one finds high beta plasma conducive to forming mirror mode waves, and hence magnetic holes.

The second interesting feature in Figure 4 is the observation that at high helio-latitude the hole count is small ($\approx 0.5/R_s$), but non-zero. Further, the hole count at $|\Phi| > 30°$is independent of latitude. Above $|\Phi| >$ 30°or so, the spacecraft sampled the streamer belt and coronal hole solar wind. At even higher latitudes, above $\approx 57°$, it is known that large-scale dynamic features, such as corotating interaction regions or coronal mass ejections, are entirely absent. Thus such features can not be the cause of the magnetic holes at high helio-latitudes.

The hole count increases in Figure 4 return to the baseline of $\approx 0.5/R_s$. Comparing the two latitude regimes in Figure 4, it appears that 90% of the holes in the ecliptic are produced by the large-scale dynamics in the solar wind, while 10% are produced by other mechanisms, ones that operate at all latitudes.

In the absence of any large-scale dynamics the occurrence of magnetic holes is not easy to explain. If they are remnants of the mirror instability , they were generated upstream from the point of observation, by an anisotropic ion population that had a plasma beta such that $\beta_{\|}/\beta_{\perp} > 1 + \beta_{\perp}$ (e.g., *Winterhalter et al.* [1994a], and references therein). This condition may exists in the near-sun environment, and it is therefore possible that the holes are relics of mirror waves generated in the corona. Alternate explanations of magnetic holes favoring the soliton approach can be found in, for example, *Baumgärtel* [1999], and *Tsurutani et al.* [1999].

An entirely different scenario for the genesis of the anisotropic ion population necessary for the mirror instability involves pick-up ions of interstellar origin. As they approach the sun, neutral interstellar hydrogen atoms are ionized via charge exchange with solar wind protons, creating the pick-up ions. When the heliospheric magnetic field is largely azimuthal at the time of ionization, the large pitch angle pick-up ions are suddenly added to the solar wind. The pick-up hydrogen is very hot, having a thermal energy up to the solar wind speed. Even though their number is very small, it may be enough to cause the mirror instability in some conditions. However, the very small density and the large scattering mean free path [*Gloeckler et al.,* 1995; *Schwadron et al.,* 1993] of the pick-up ions call into question their effectiveness to produce features on the scale of the magnetic holes. This possibility will be pursued in future work.

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**Figure 1.** Two examples of magnetic holes. The events have in common that $B_{min}/B_0 < 0.5$, and $\delta\theta < 5°$(linear holes). $\delta\theta$ is the maximum angle of the field rotation across the hole, which has a minimum value of $B_{min}$ in an average field of $B_0$.

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**Figure 2.** Ulysses' trajectory during the "fast latitude scan" interval.

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**Figure 3.** The number of holes per day versus heliographic latitude and time during the fast latitude scan interval. Only "linear" holes ($\delta\theta < 10°$) are counted.

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**Figure 4.** The latitude dependence of magnetic holes. The number of holes per solar radius (lower trace, left scale), and the solar wind speed (upper trace, right scale) versus heliographic latitude. Note the small, but relatively constant $N/R_s \approx 0.5$ at latitudes above $\approx 30°$, where the solar wind speed is high.

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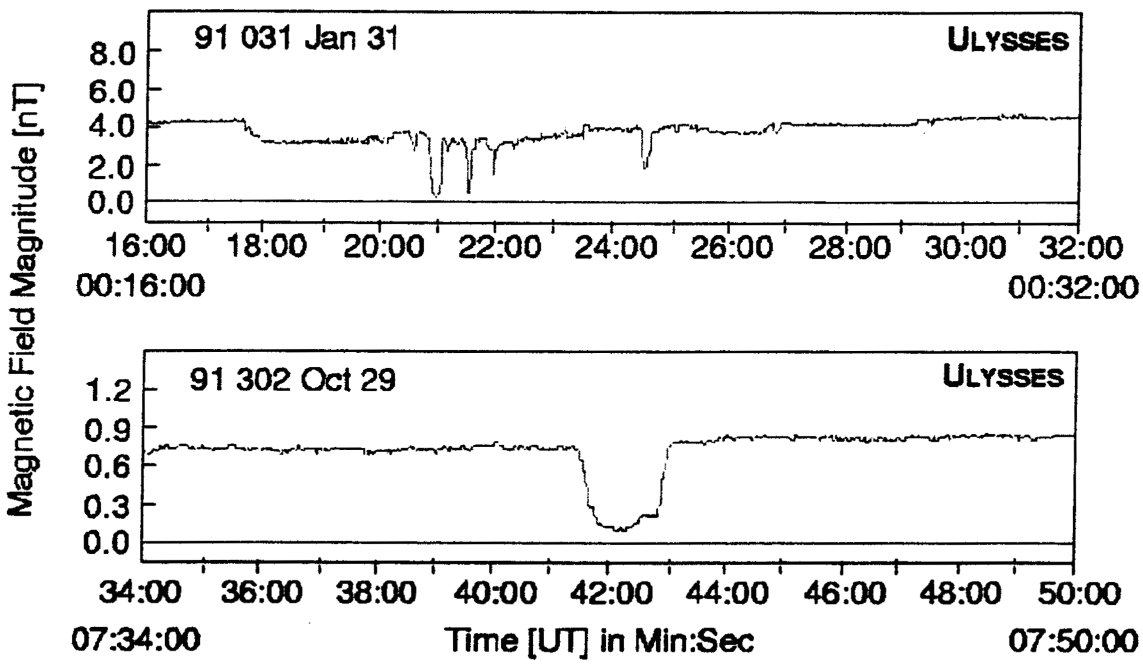
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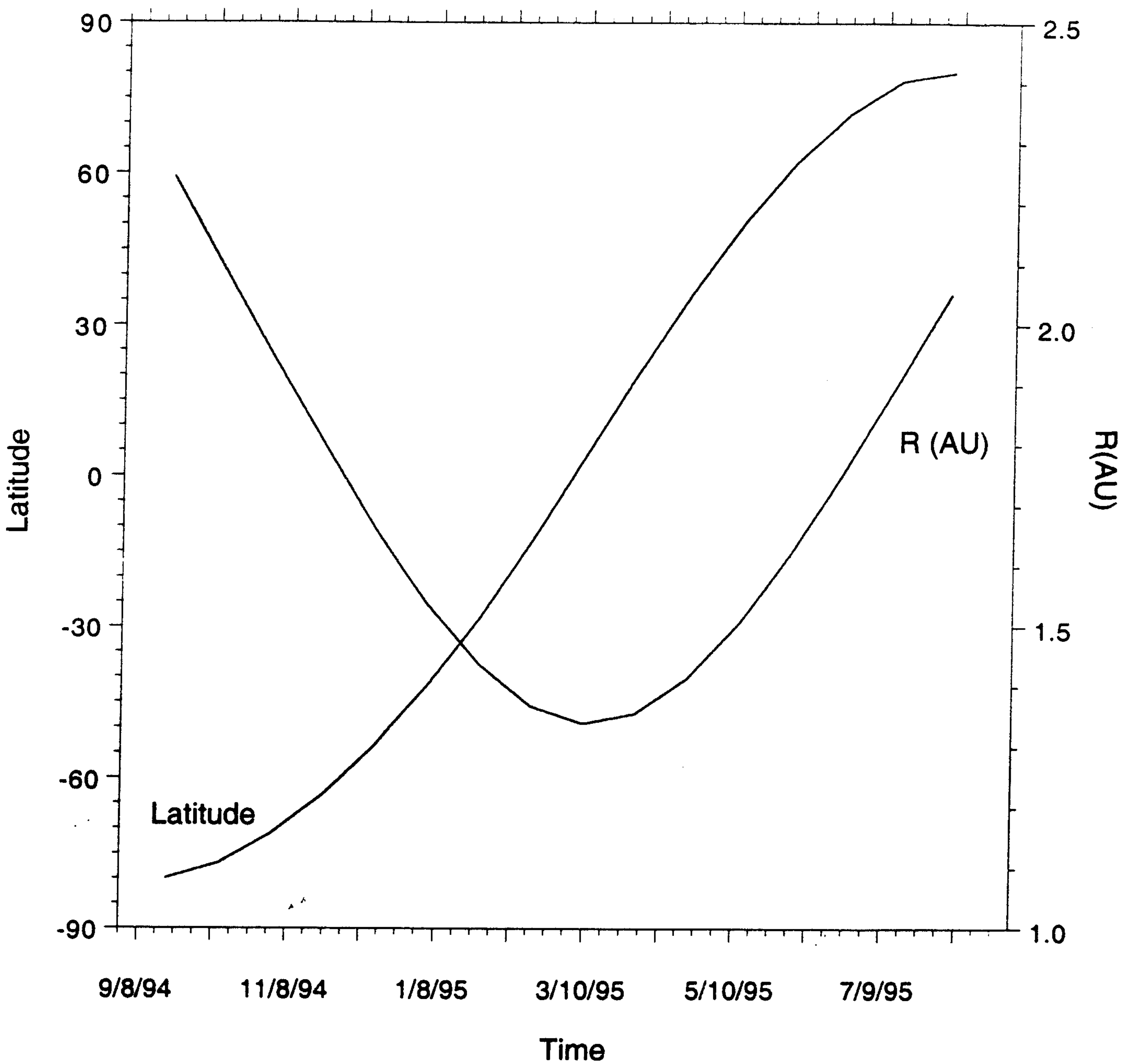
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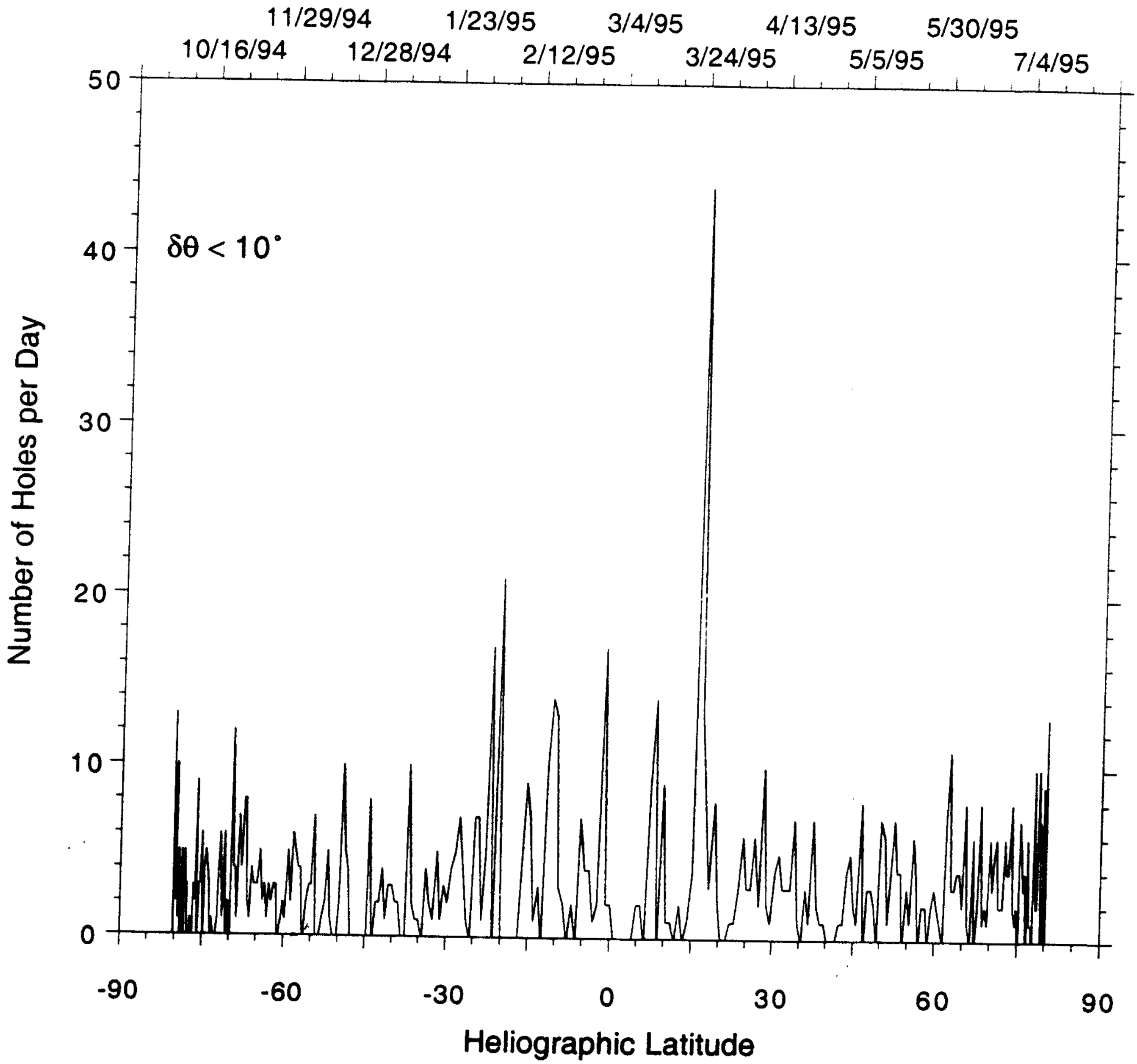

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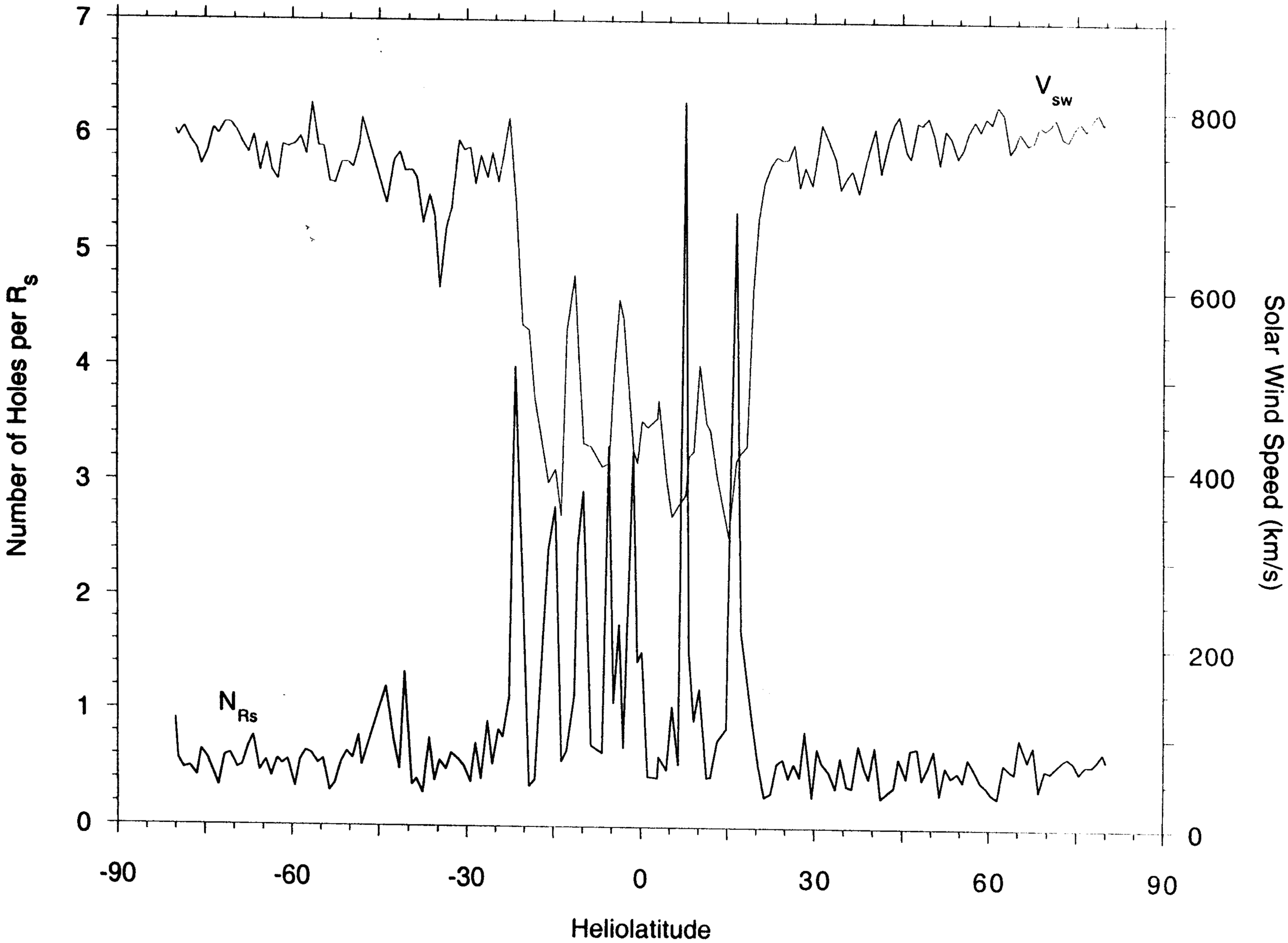

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